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Designing a sample return mission to an asteroid

The Example of Hayabusa Series

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Abstract

There is no established way to "design an asteroid sample return mission". This is because the design includes complicated iterative process that requires a variety of knowledge of in both science and engineering.

In this lecture, after introduction, mission overview and key designs are introduced for Hayabusa(HY)-1, by which you will learn what a asteroid sample return mission is like.

After that, to experience a design iteration, another example, HY-2 is used to know the mission profile as a reference/base-line.

Contents

1. Introduction

Strategy for Solar System Exploration at ISAS

1. After HY1, growing interest in origin of life, in particular chemical precursors for life in early solar system: their distribution and transfer toward inner solar system.
   - strong interest in sample & return from small bodies (asteroid, comet and planetary moon): ***1st Sub-Program***
2. Starting from Akatsuki, planetary exploration is the next logical step for us for unveiling atmospheric/magnetospheric environment and the surface environment of planets.
   - strong interest in planetary landing, in particular Mars: ***2nd Sub-Program***

Asteroid Sample Return Mission
Science Goals

To know the origin and evolution of the solar system

Asteroids are key objects relatively well conserve their past

Global map of material distribution in the whole asteroid belt

Huge databases based on ground-based observations:

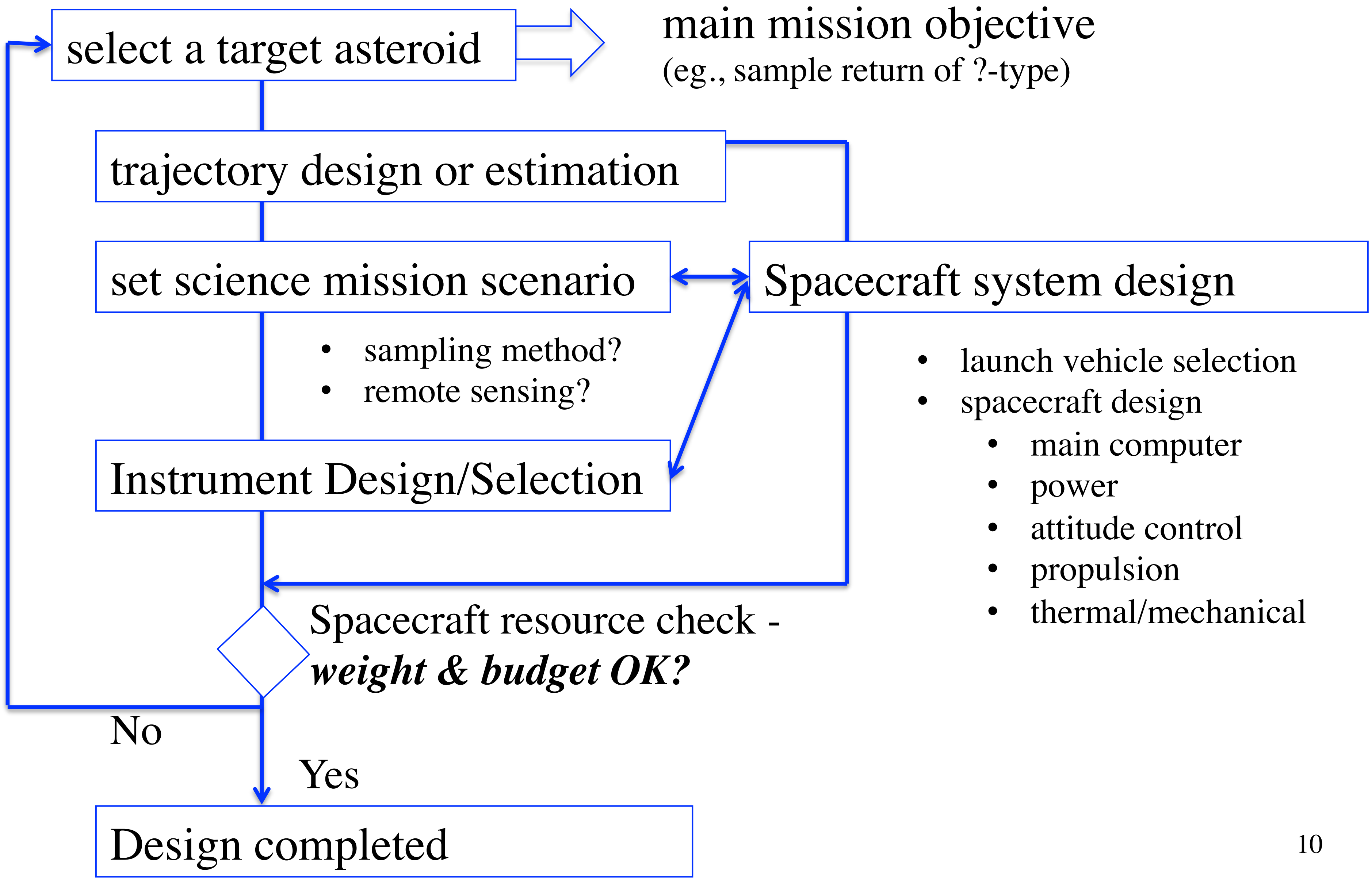
taxonomic types of asteroid

if Correlated by Returned Sample

Huge databases based on meteorite researches:

material species of meteorite

Asteroid Mission Design Loop



2. Hayabusa-1, Mission Outline and Achievements

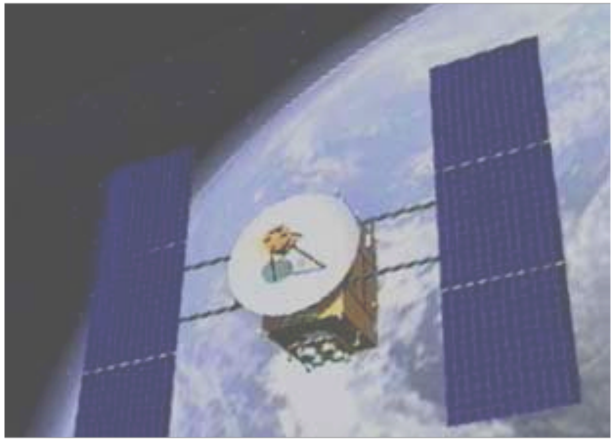
to learn typical asteroid sample mission and its basics

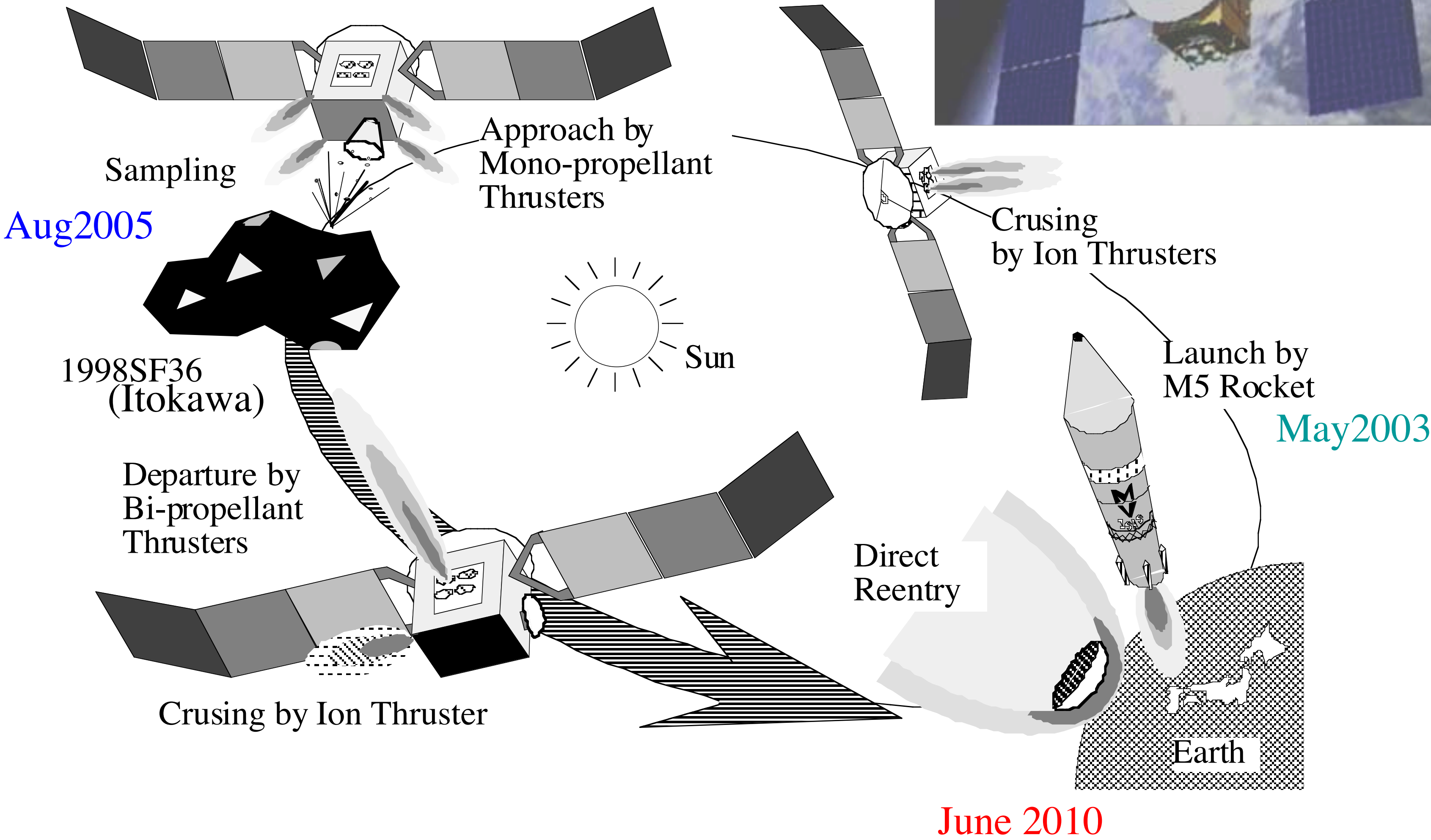
Asteroid Explorer MUSES-C Hayabusa (HY1) Objectives

MUSES-C: MU Space Engineering Satellite-C

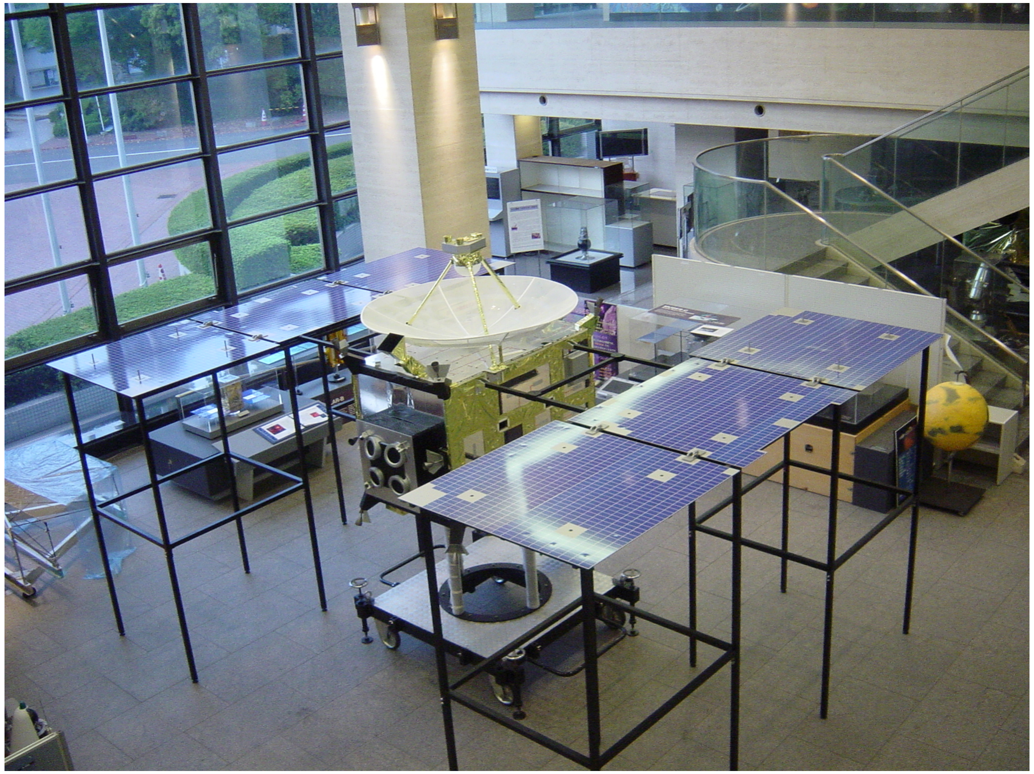
1. the use of ion engine as a primary means in the interplanetary field propulsion
2. an autonomous guidance and navigation scheme utilizing optical observations
3. a robust and promising surface sample collection mechanics
4. the direct reentry from an interplanetary trajectory for sample recovery on the ground

MUSES-C (Hayabusa-1) Mission Sequences



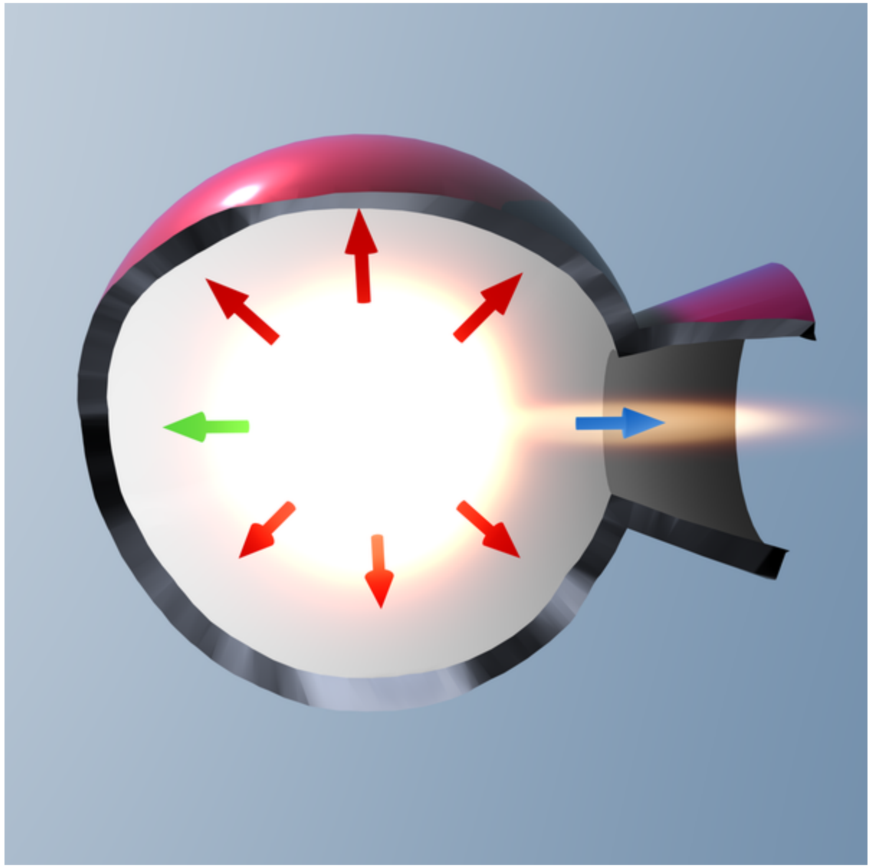


Asteroid Explorer MUSES-C Hayabusa (HY1)



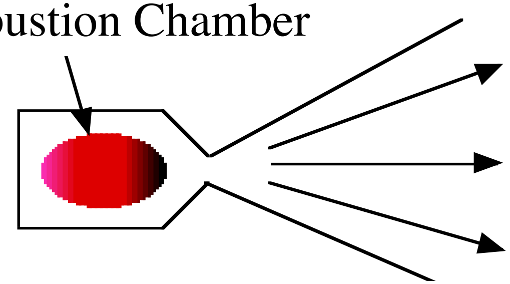
Dimensions：1.0m x 1.6m x 1.1m
Weight : 380kg(Dry)
Chemical Fuel 70kg
Xe Propellant 60kg
Total 510kg
Electric Power : 2.6kW@Earth

Principle of Rocket Propulsion



- A rocket engine is a type of jet engine that uses only stored rocket propellant mass for forming its high speed propulsive jet.
- Combustion is used for practical rockets, as high temperatures and pressures are desirable for the best performance.

Thrust and Isp by Rocket Engine



Thermal energy to velocity energy conversion via nozzle

$$F = \dot{m}\, u_e \qquad (1)$$

$$Isp = u_e / g \qquad (2)$$

F: Thrust (N)

$\dot{m}$: Mass flow rate(kg/s)

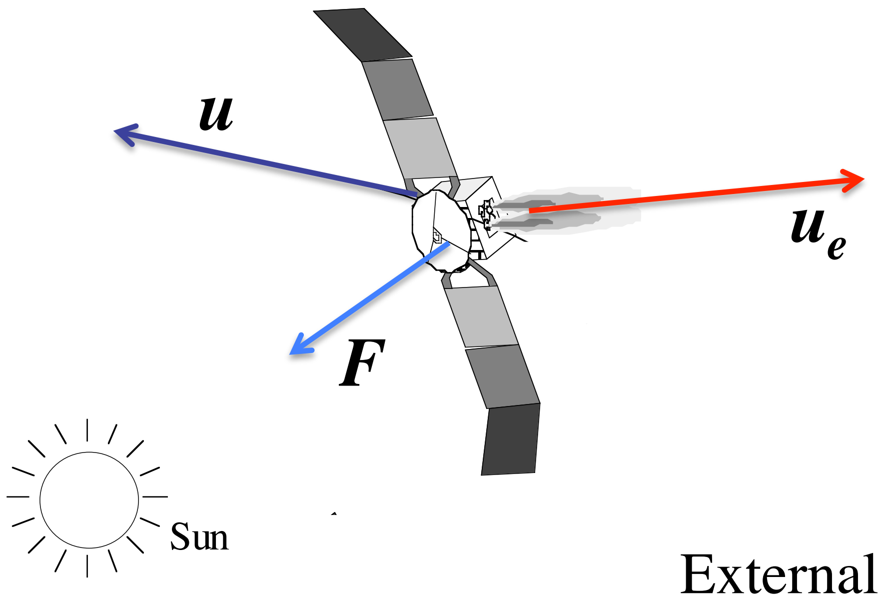
u_e : Velocity (m/s)

Isp: Specific Impulse (s)

corresponds to fuel efficiency（Large Isp is fuel efficient＝large force with only small amount of fuel）

g: (9.8m/s^2)

Motion of Interplanetary Spacecraft(S/C)

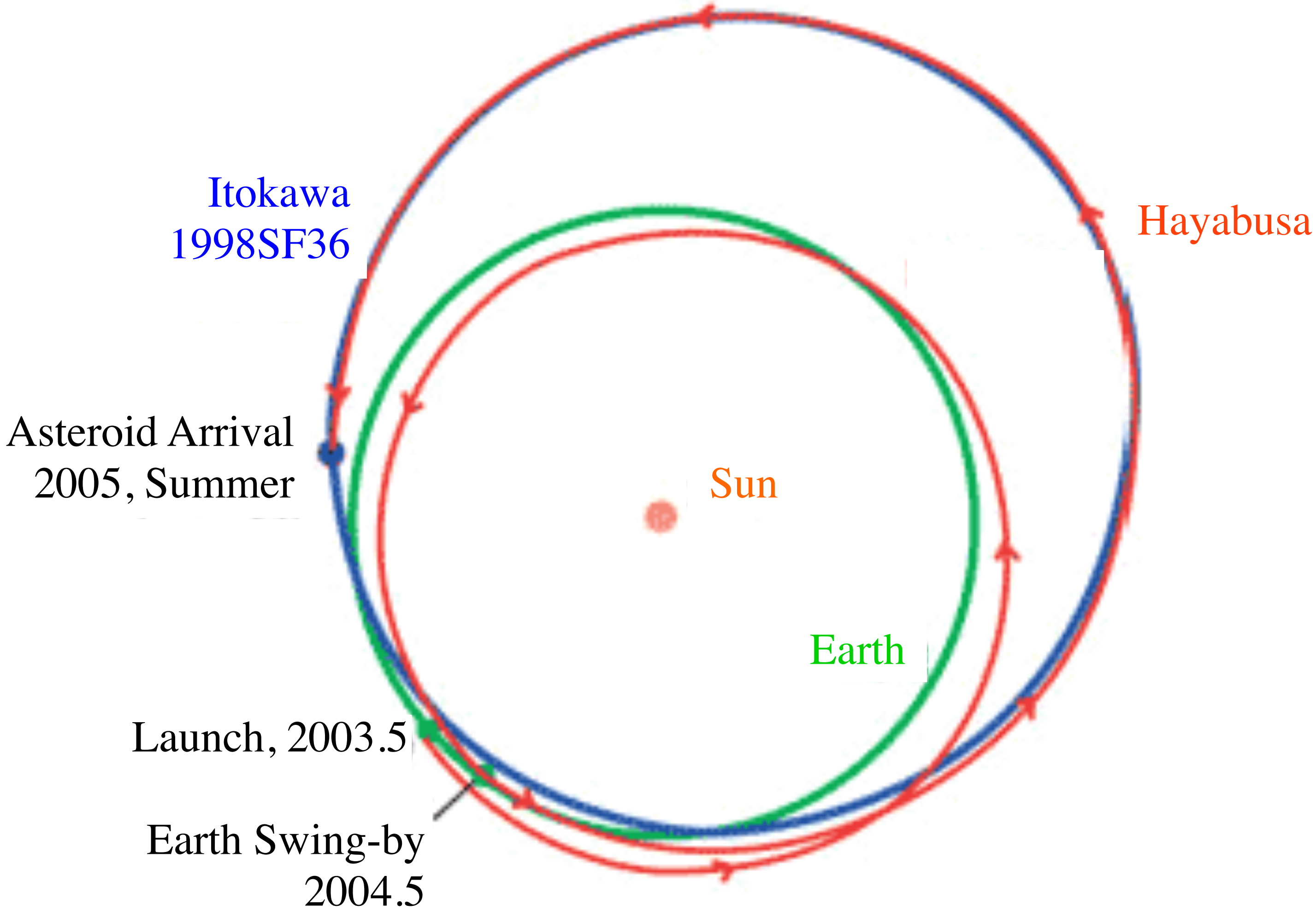


External force
(eg., gravity force)

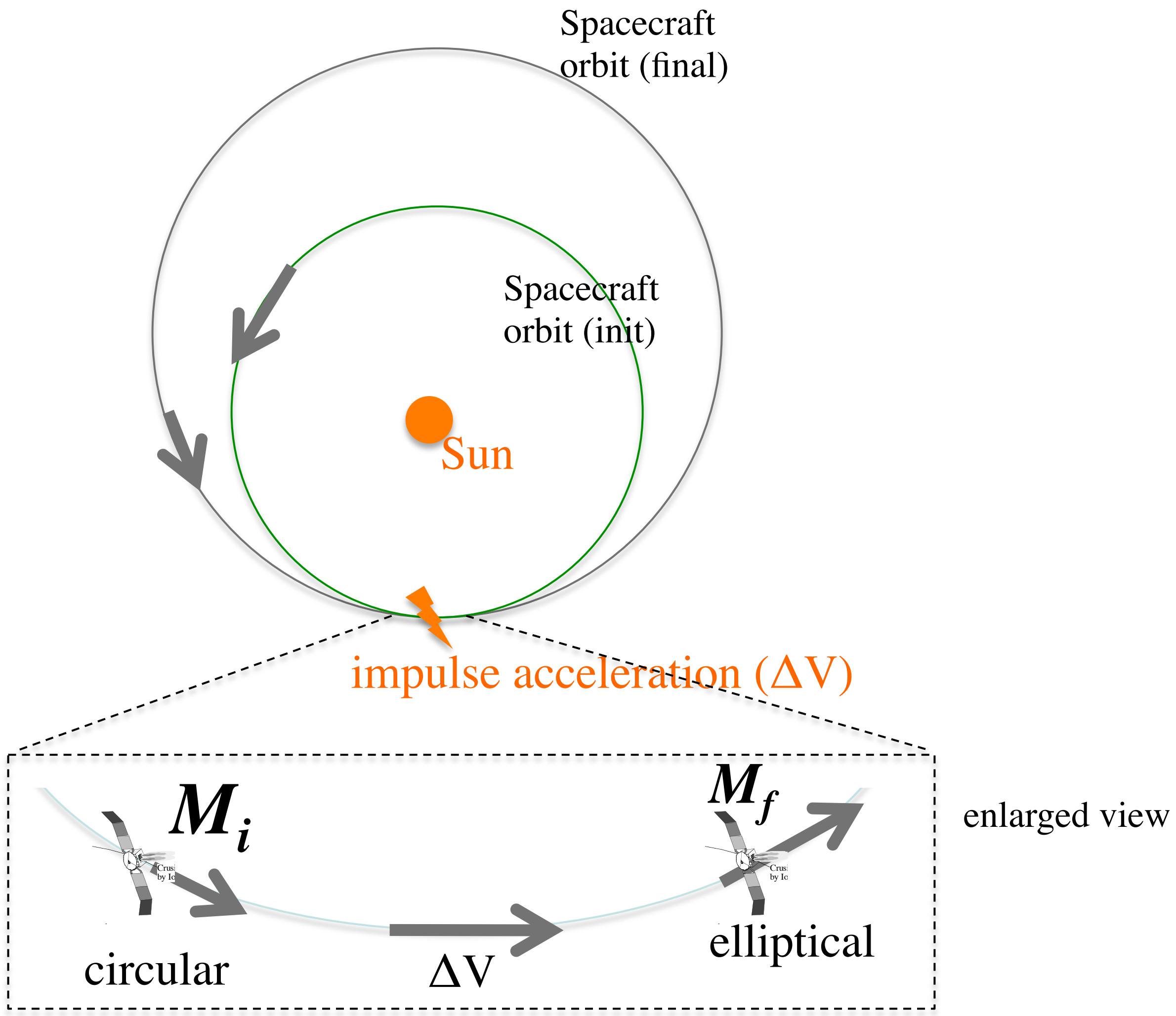
Equation of motion of S/C :

$$m\frac{d\boldsymbol{u}}{dt} = \boldsymbol{F}$$

Hayabusa's Trajectory before Arrival to Itokawa



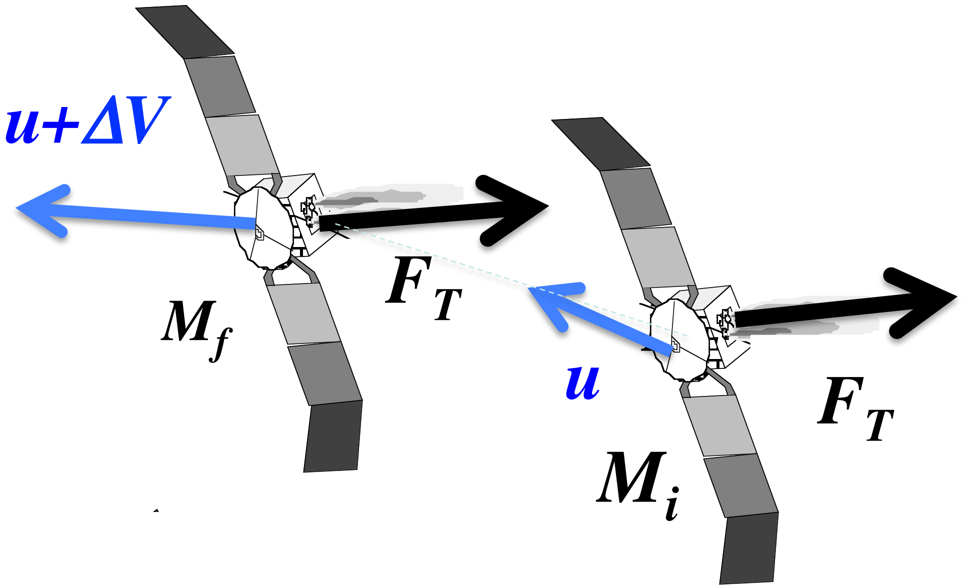
Orbital Transfer ΔV (conceptual view)



transfer from circular to elliptical orbit

Deriving S/C Mass Budget for Isp and ΔV

Rocket Equation



Motion of S/C:

$$m\frac{d\boldsymbol{u}}{dt} = \boldsymbol{F}_T$$

$$= -\left|\frac{dm}{dt}\right|\boldsymbol{u}_e$$

With assumtpion of dm/dt >0,

$$du = -u_e\frac{dm}{m}$$

With initial mass=M_i, final mass=M_f, the equation of velocity increment（ΔV）（rocket equation）is derived:

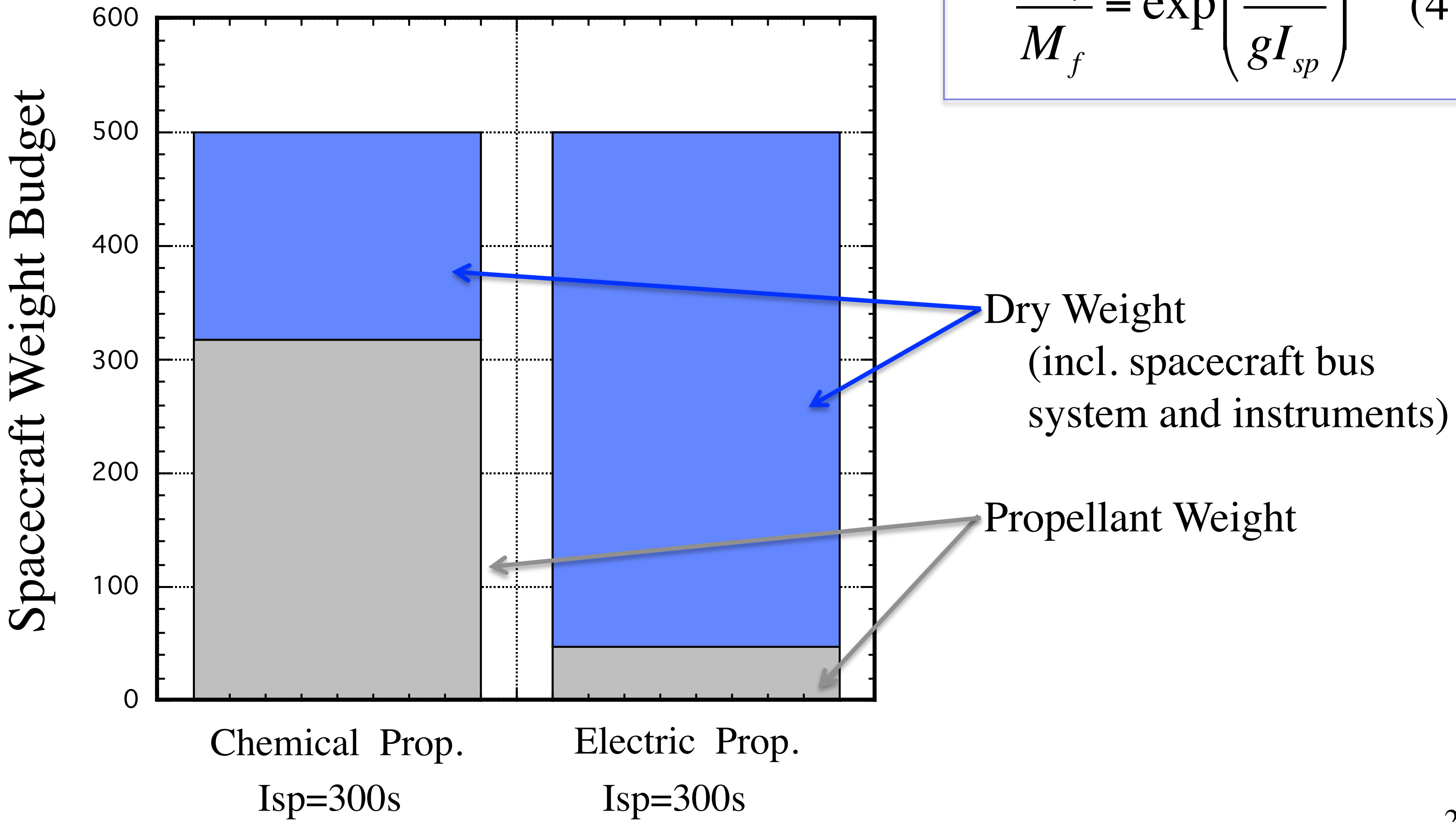
$$\Delta V = u_e \ln\frac{M_i}{M_f} \quad (4)$$

$$\frac{M_i}{M_f} = \exp\left(\frac{\Delta V}{gI_{sp}}\right) \quad (4')$$

S/C Mass Budget for Isp and ΔV

derived from Rocket Equation

$$\frac{M_i}{M_f} = \exp\left(\frac{\Delta V}{g I_{sp}}\right) \qquad (4')$$

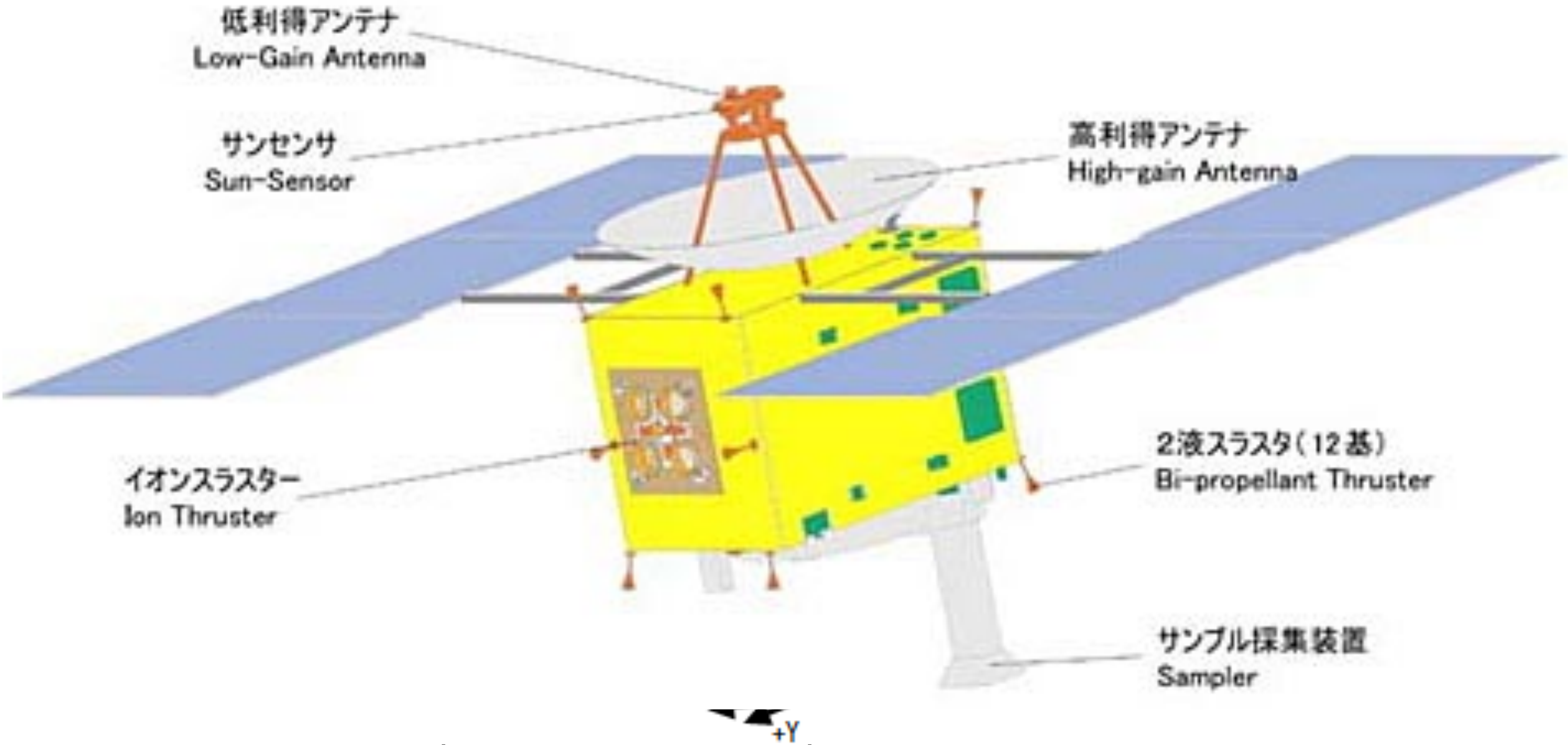


Major Thrusters available for Spacecraft

	Propellant	Thrust	Isp
mono-propellant thruster	H_2H_4	0.1~20 N	~210s
bi-propellant thruster	MMO, N_2O_4 , H_2H_4+N_2O_4	1~500 N	~320s
cold gas jet	$N_{2,}$ Xe	~1 N	100s
EP	Xe, H_2H_4 etc.	~150 mN	350~3000s

- Hayabusa used both bi-propellant thruster and EP (ion engines)

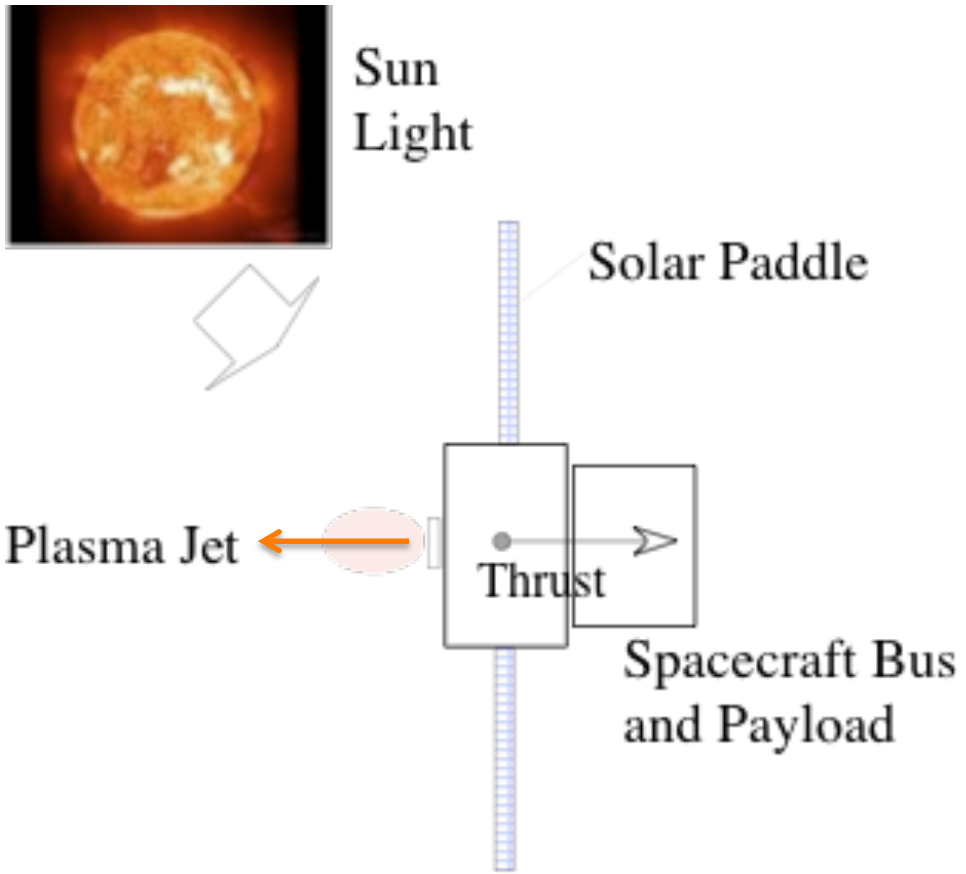
Hayabusa and its Propulsion and Attitude Control System



- RCS（Reaction Control System）consists of bi-propellant (N_2H_4+NTO) 20N thruster with 12 units. They were used for both attitude control and some orbital controls.
- Weight: RCS=41kg(+prop.67kg), Ion Engine =61kg(+prop.70kg)
- Three Reaction wheels were also used for attitude control

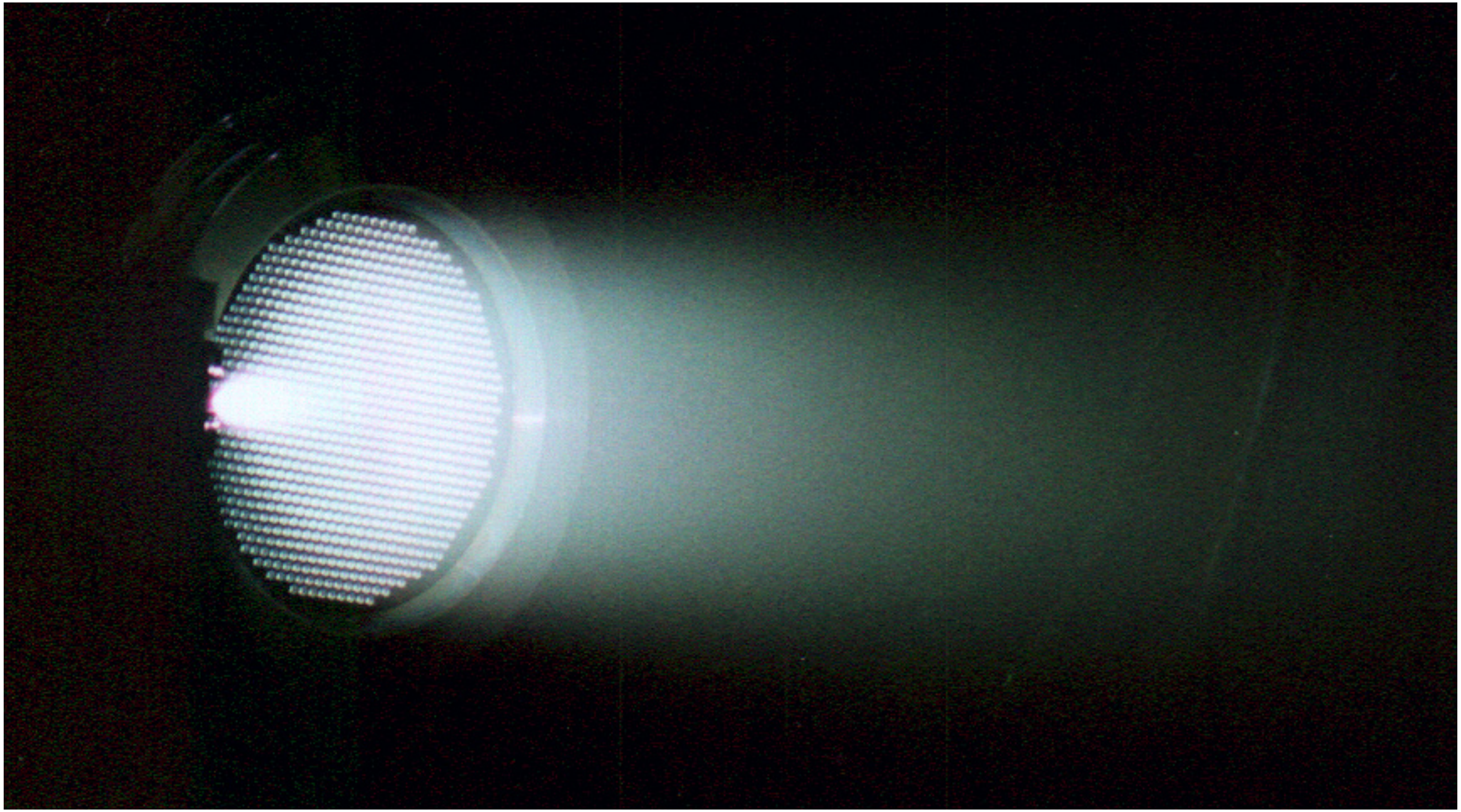
Principle of Solar Electric Propulsion (SEP)

Accelerate fuel by power from solar paddle onboard S/C
→EP produces much higher exhaust velocity in comparison with chemical thrusters



Concept of Solar Electric Propulsion (SEP)

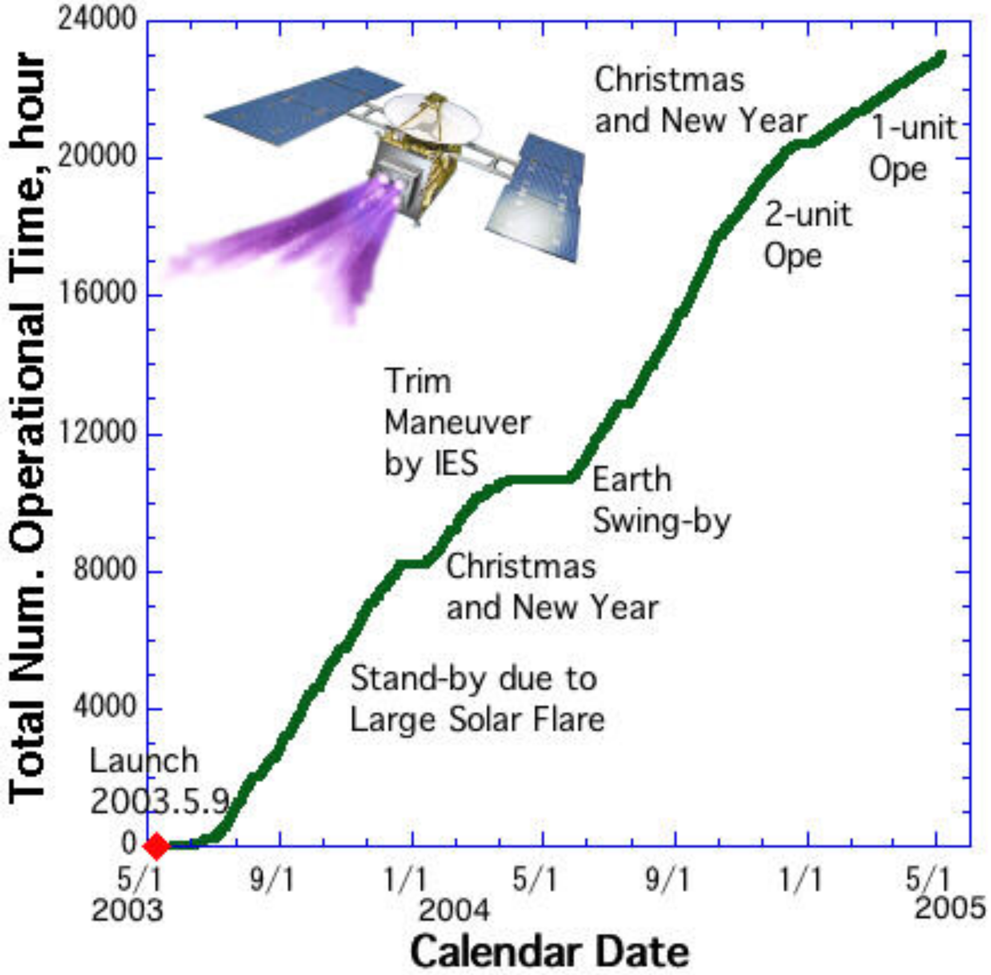
Ion Engine Operation in Vacuum Chamber



Mu-10 Ion Engine Prototype Model（10cm/8mN/400W）

Ion Engine Operation in Space (HY1,cont)

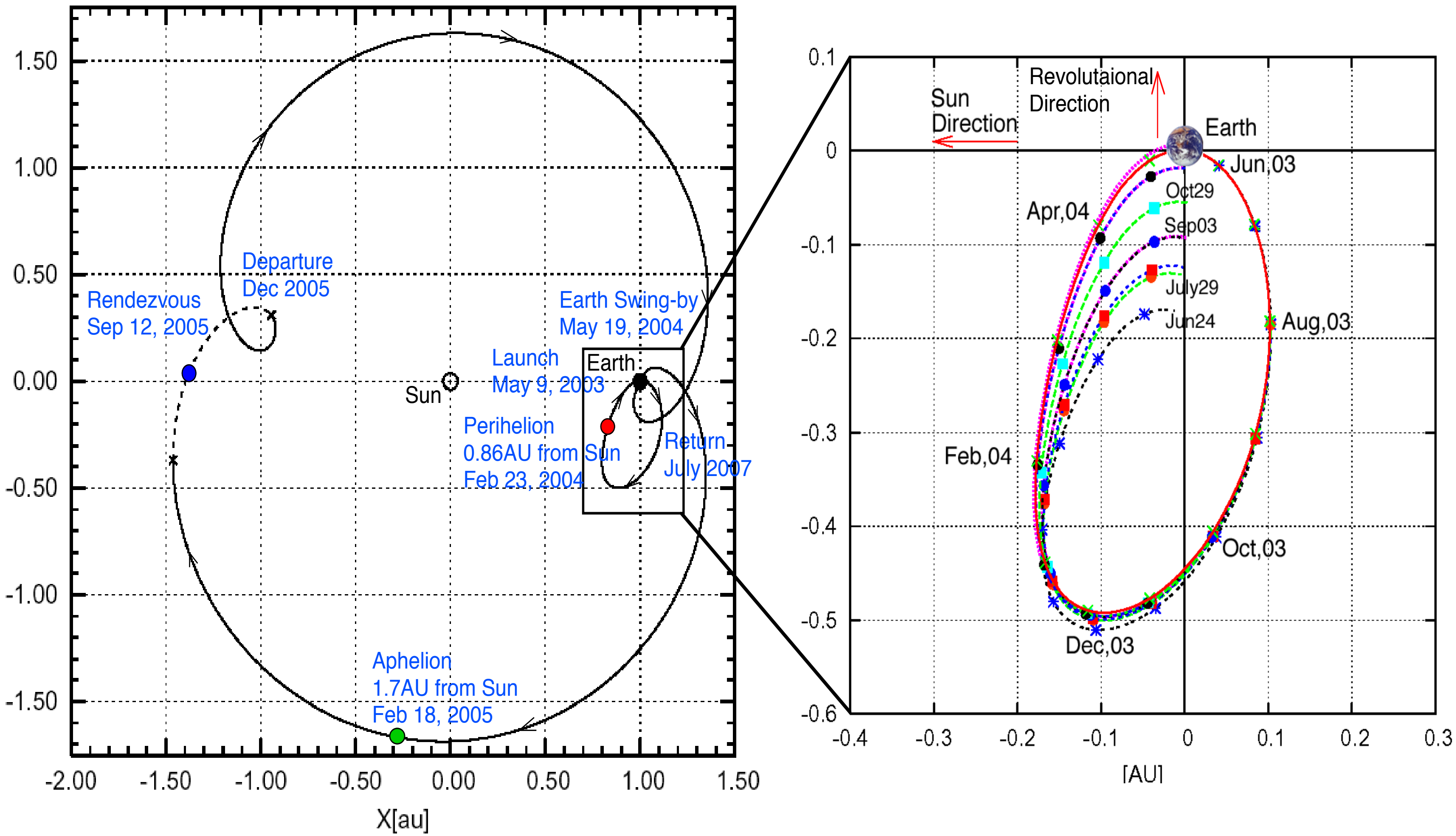
Operation History up to Itokawa



The ion engines aboard Hayabusa had been operated by Aug 28th, 2005, the total operation of 26,000 hours was successfully performed. The engines were driven to generate about 1,400m/s delta-V with 22kg xenon propellant.

Hayabusa Trajectory in Sun-Earth Fixed coordinate

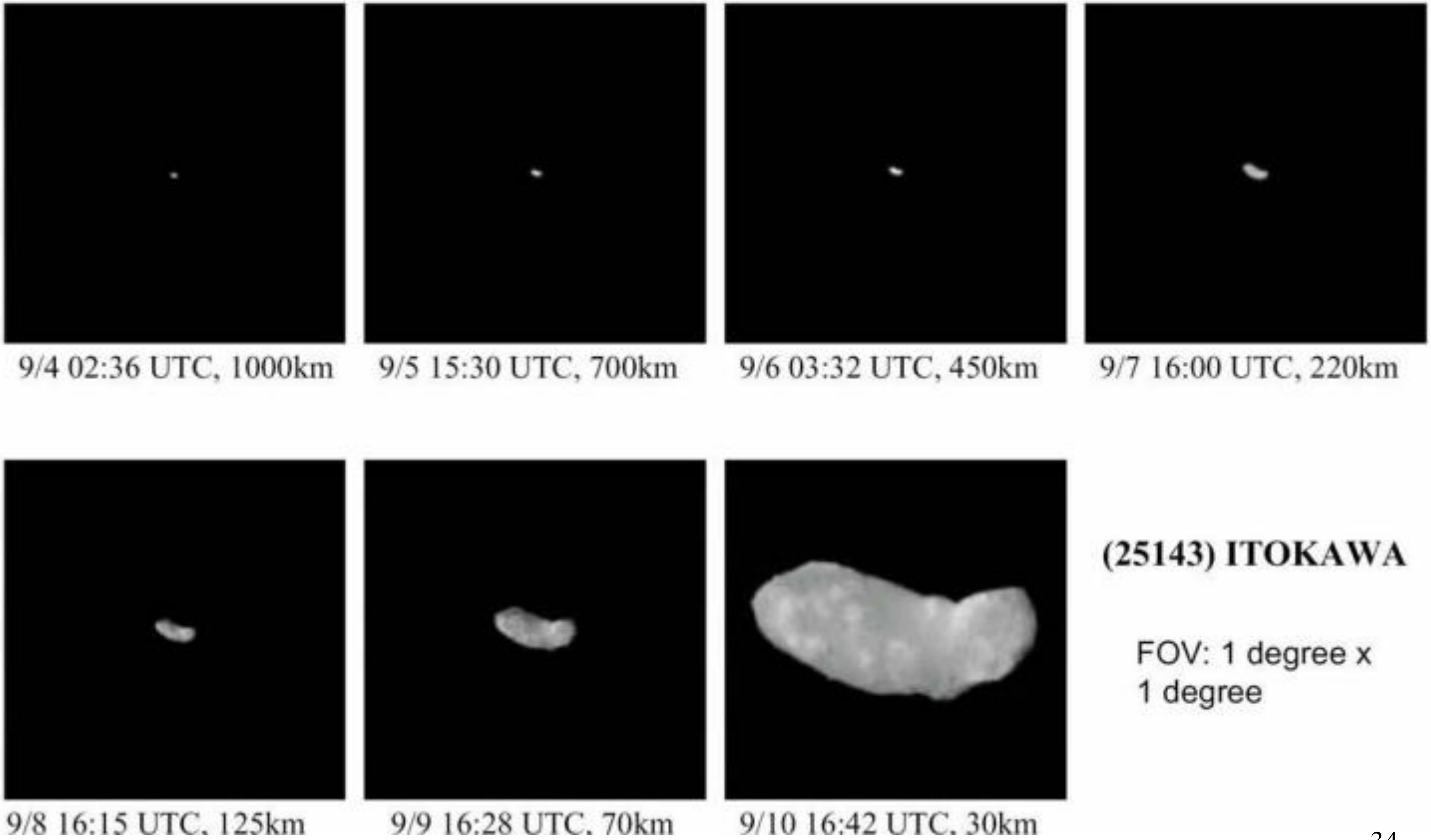
EPΔVEGA toward Asteroid ITOKAWA



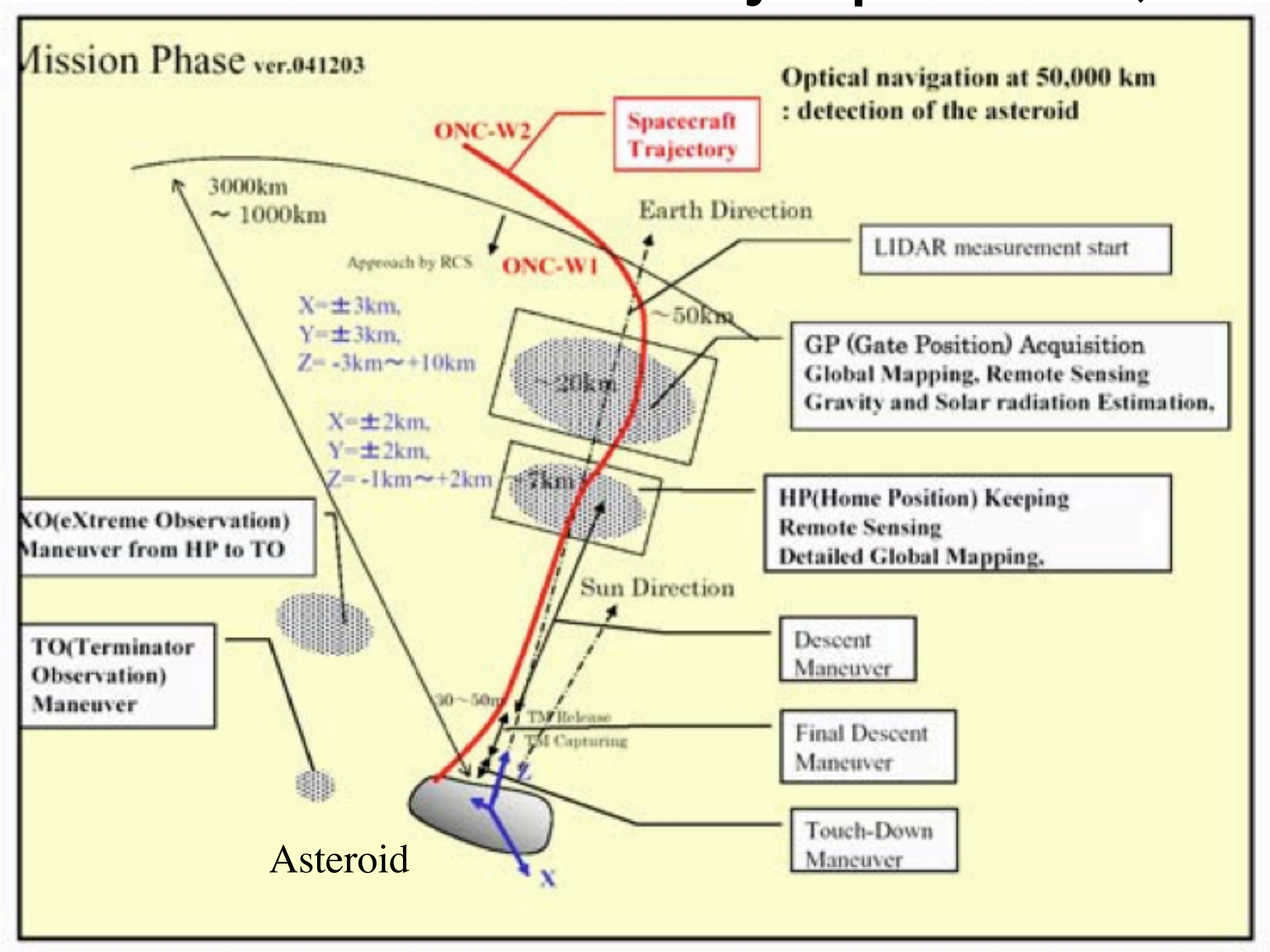
HAYABUSA as SEP run outward journey between 1.7AU outer and 0.86AU inner in solar distance.

Hayabusa Arrival to Itokawa

Rotating Asteroid ITOKAWA is getting bigger

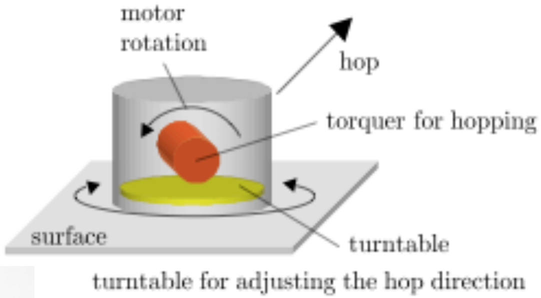


Asteroid Itokawa Proximity Operation (HY1)



Asteroid Itokawa Proximity Operation (HY1)

MINERVA micro rover



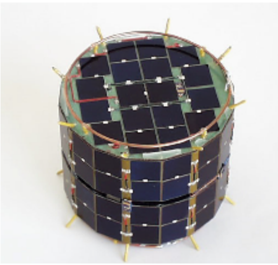
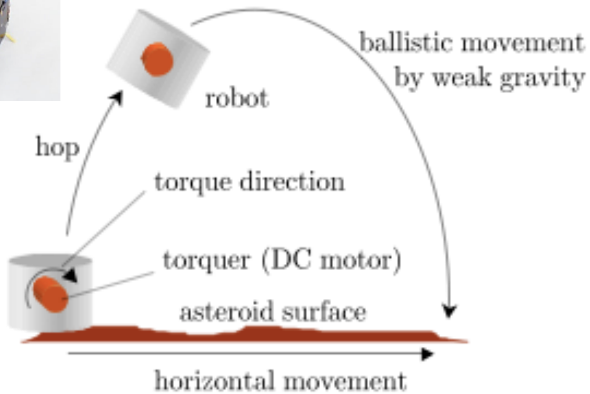
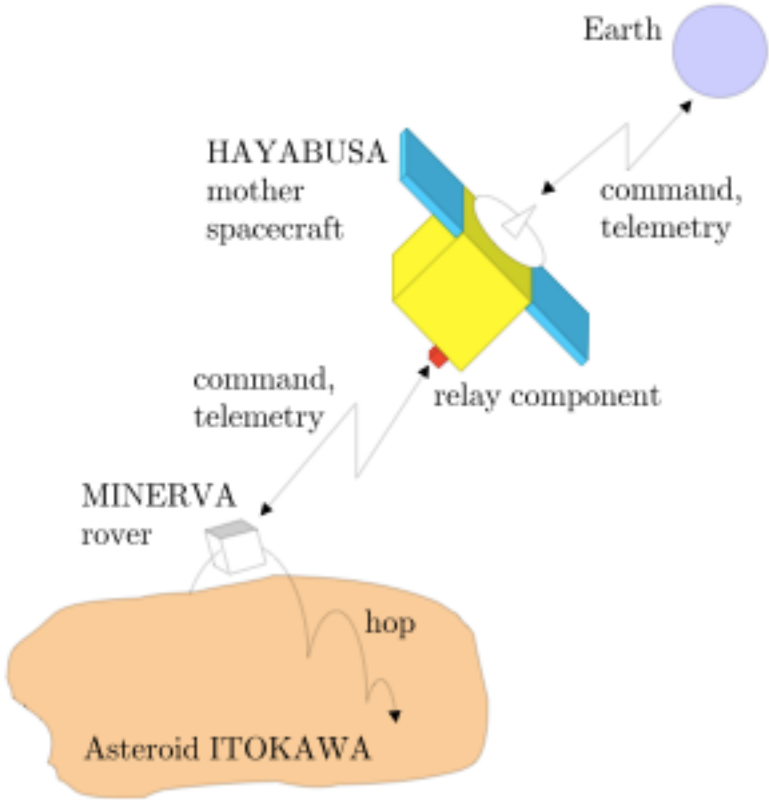


Fig.4 Turntable structure





MINERVA's Hopping mobile system by torquer and mission sequence

- This solar-powered vehicle was designed to take advantage of Itokawa's very low gravity by using an internal flywheel assembly to hop across the surface of the asteroid.
- MINERVA was deployed on 12 November 2005, but unfortunately it could not reach at the asteroid.

Hayabusa-1 Science Instruments

AMICA - Asteroid Multiband Imaging Camera

- Map surface morphology including surface features to one 1-m resolution
- Determine spin state, colors, size, shape, volume, and rotation characteristics
- Search for possible asteroid satellites and dust rings
- Establish a global map of surface features and colors
- Reveal history of impacts from other asteroid and comet fragments
- Determine optical parameters of regolith particles using polarization degree vs. phase curve at large phase angles
- Map mineralogical composition of asteroid and identify rock types present
- Determine most likely meteorite analog for composition of asteroid

Near-IR Spectrometer

- Map mineralogical composition of asteroid and provide main evidence for rock types present on surface at scales as small as 20 m
- Characterize surface heterogeneity
- Together with elemental composition measurements provided by (XRS) and color imagery from camera, IR spectrometer will provide link between this asteroid and a meteorite type

Hayabusa-1 Science Instruments

X-Ray Spectrometer (XRS)

- Map the major elemental composition of the surface as the asteroid rotates under the spacecraft
- Determine the major elemental composition at localized areas during asteroid approach phases
- Measure surface composition accurately enough to establish relationship between asteroids and meteorites and identify type of meteorite to which asteroid is linked
- Provide elemental abundance maps to investigate inhomogeneity of regolith

Sample Return Analysis

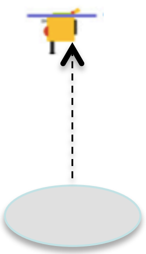
- Samples returned to Earth will provide a detailed and definitive elemental composition analysis of the asteroid's surface materials and hence forge an unambiguous link between the asteroid's composition and a meteorite type

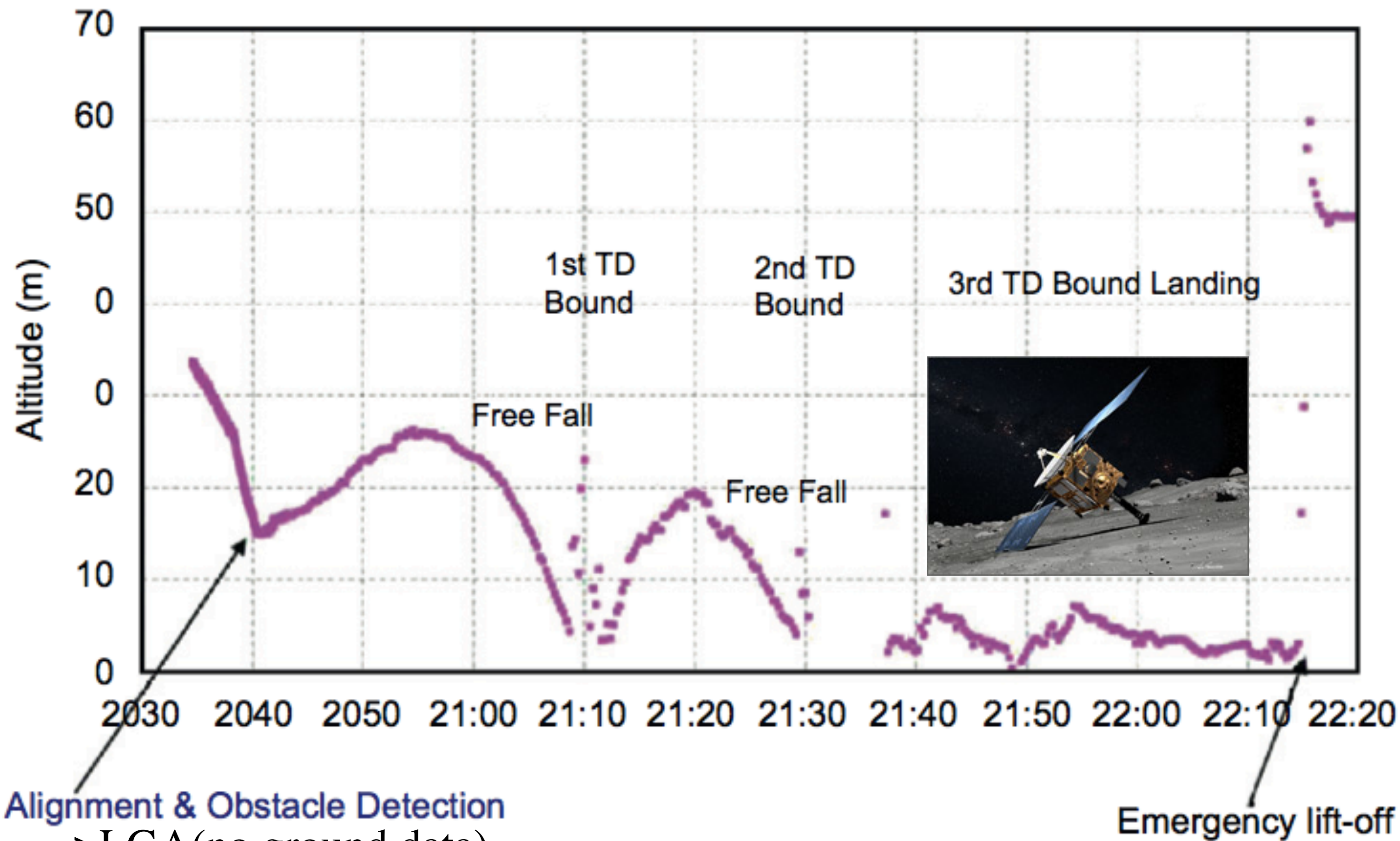
LIDAR

- Provide accurate shape and mass determinations for asteroid
- Map asteroid's surface with a maximum resolution of about 1-meter

Asteroid Itokawa Proximity Operation (HY1)

1st Touchdown on 20th Nov., 2015



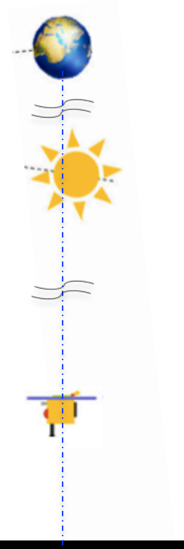


UTC

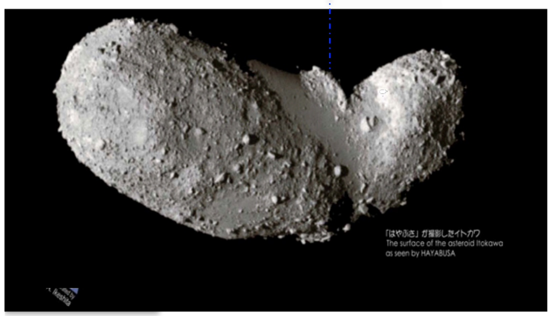
->LGA(no ground data)

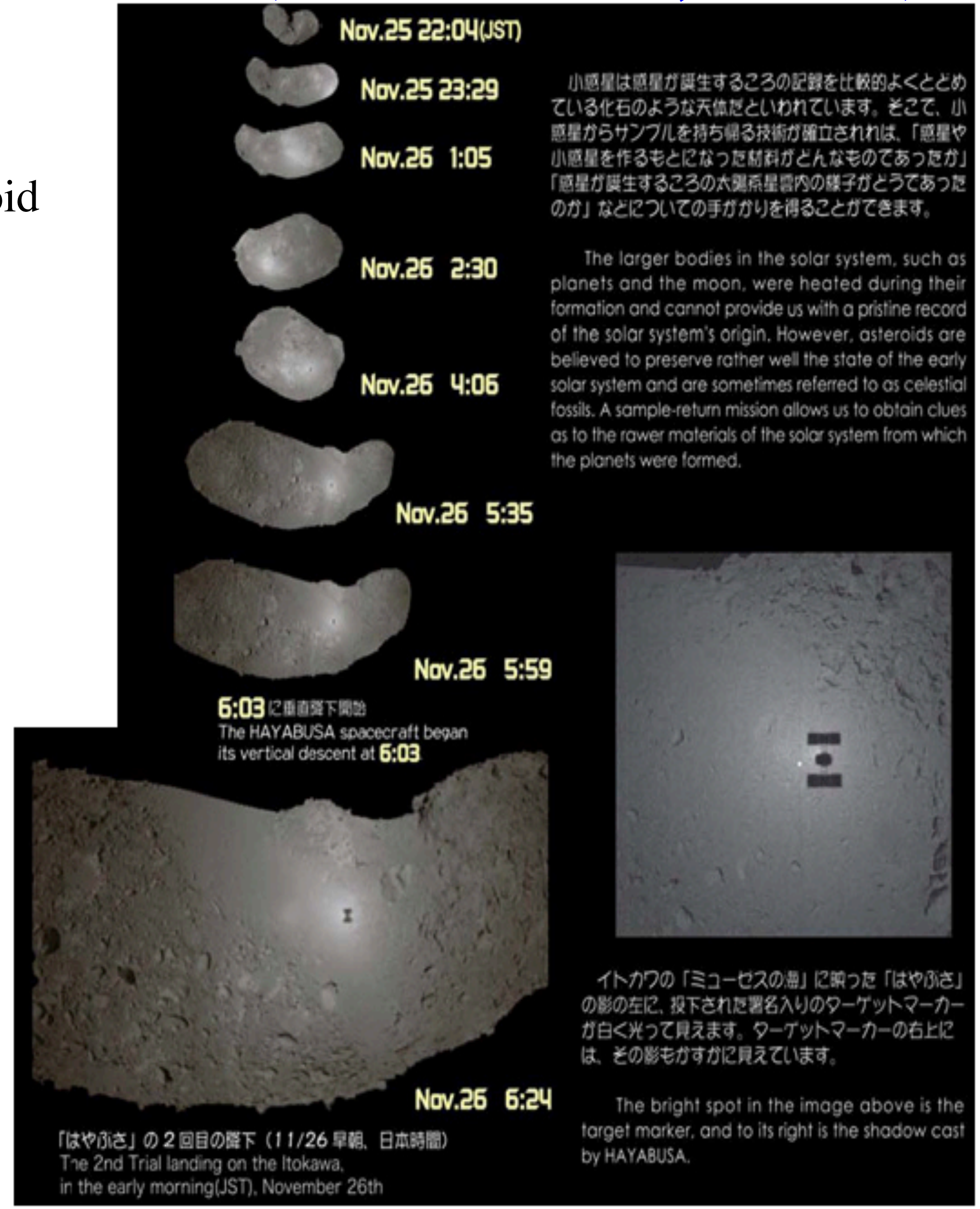
Laser Range Finder (LRF) data during 1st touch down

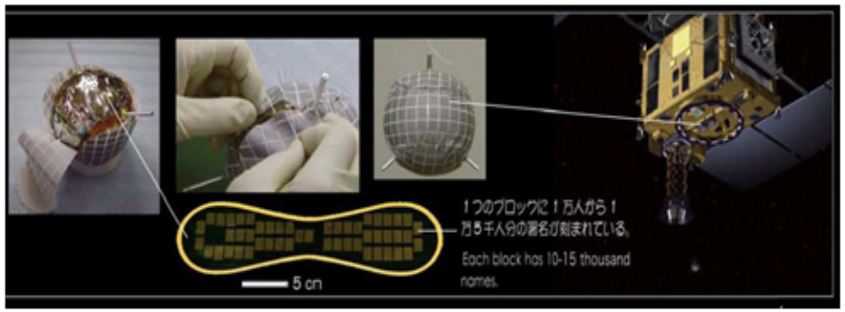
HY1 Itokawa Touch down(Nov.19/25, 2005)



earth-sun--S/C-asteroid
appr. stay in a line



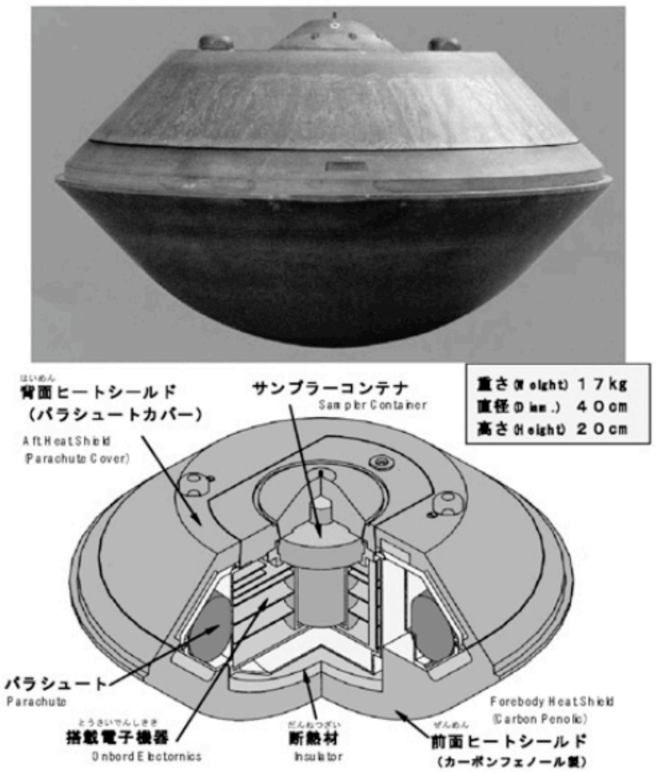




Failure after 2nd Touchdown

2005, Nov. 26	2nd Touchdown
2005, Nov. 27	RCS failure, Hayabusa is spinning at ~7deg/s rate
2005, Nov. 28	Loss of communication with Hayabusa
2005, Nov. 29	Recovery of communication but without HK
2005, Nov. 30	Communication with Hayabusa only with beacon
2005, Dec. 1	Continuous leakage of RCS Fuel, Comm. with HK due to low spinning rage.
2005, Dec. 2	RCS uncontrolable, Apparent nutation motion
2005, Dec. 8	Communication black out
	（Spin precession beyond critical nutation angle. Power breakdown is expected.)
2005, Dec. 9～	Recovery operation started (sending so may reboot command to Hayabus)
2006, Jan. 24～	Communication Signal captured。 Spacecraft with pure spin motion ~7deg/s）
2006, Feb. 6～	Attitude control with Xenon Jet started （RCS fuel empty）
2006, Mar. 1	Communication with HK telemetry recovered.

Super-orbital Reentry of Hayabusa's Capsule



Hayabusa Reentry Capsule

Velocity(12km/s)、Structure(50G)、Heat shield(40MJ/kg)

Yamada, and Abe, J. Plasma Fusion Res (2006)

Hayabusa Capsule Reentry Sequence

3. Hayabusa-2, Mission/System Design and Plan

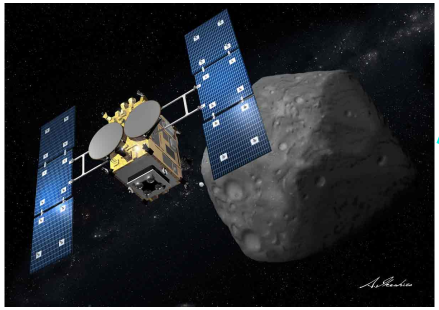
to learn a base-line to start-up new mission

Hayabusa-2 Mission Outline

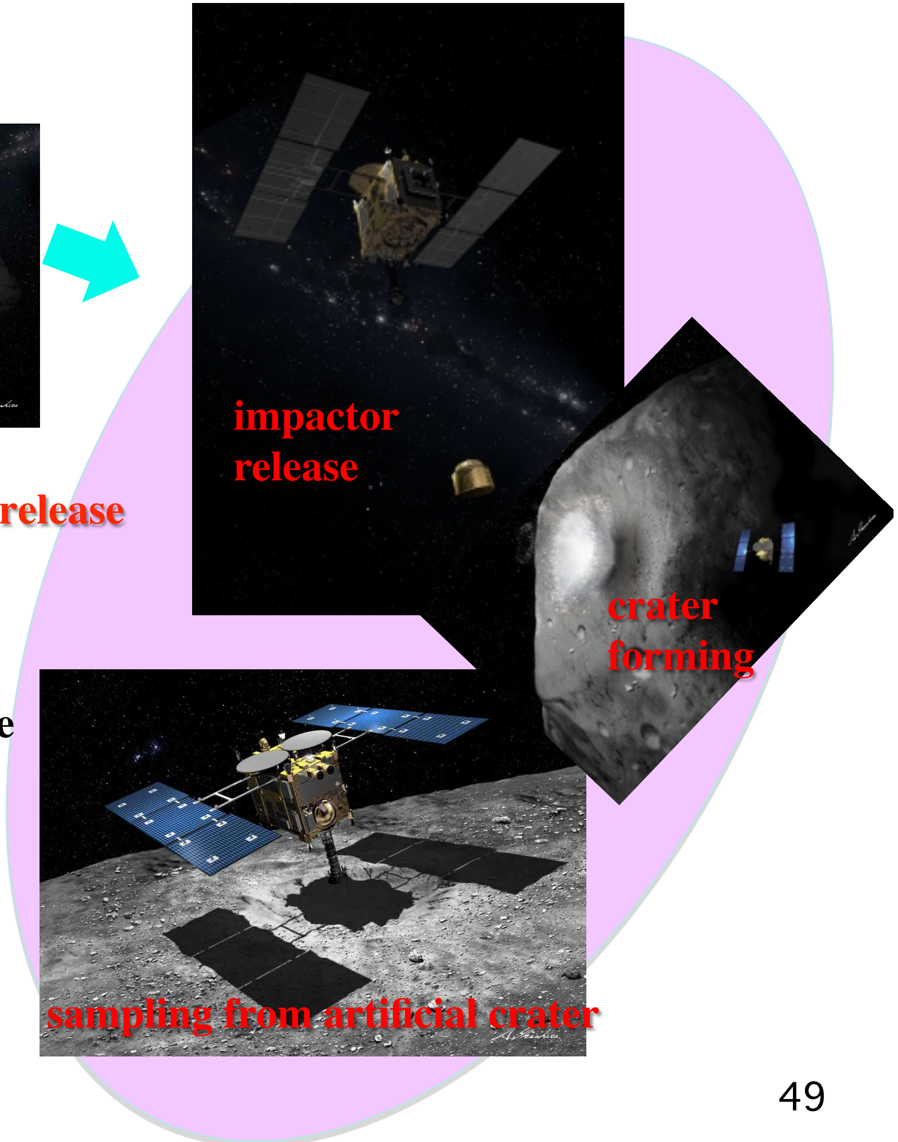
Launch
Dec.3, 2014

Earth Swing-by
Dec.3, 2015

Asteroid (1999JU3) Arrival
Jun.-Jul. 2018

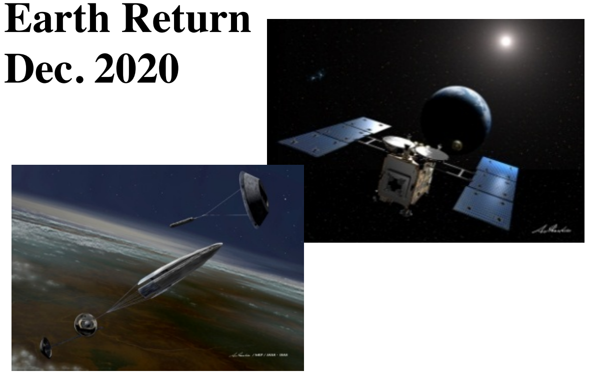


- **asteroid remote sensing**
- **small rovers and lander release**
- **multiple samplings**



Departure
Dec. 2019

Earth Return
Dec. 2020



HY-2 Spacecraft

Engineering and Science Payload of HY-2

Payloads	Specifications
Multiband Imager (ONC-T)	Wavelength: 0.4 – 1.0 μm, FOV: 5.7 deg x 5.7 deg, Pixel Number: 1024 x 1024 px filter (ul, b, v, w, x, p, Wide) (Heritage of Hayabusa)
Near IR Spectrometer (NIRS3)	Wavelength: 1.8 – 3.2 μm, FOV: 0.1 deg x 0.1 deg (Heritage of Hayabusa, but 3μm range is new)
Thermal IR Imager (TIR)	Wavelength: 8 – 12 μm, FOV: 12 deg x 16 deg, Pixel Number: 320 x 240 px (Heritage of Akatsuki)
Laser Altimeter (LIDAR)	Measurement Range: 30 m – 25 km (Heritage of Hayabusa)
Sampler	Minor modifications from Hayabusa-1 (Heritage of Hayabusa)
Small Carry-on Impactor (SCI)	Small system released form the spacecraft to form an artificial crater on the surface (New)
Separation Camera (DCAM)	Small, detached camera to watch operation of Small Carry-on Impactor (Heritage of IKAROS)
Small Rover s (MINERVA II-1, II-2)	Similar to MINERVA of Hayabusa-1 (possible payload: Cameras, thermometers) (Heritage of Hayabusa)
Small Rover (MASCOT)	Supplied from DLR & CNES MicrOmega, MAG, CAM, MARA

Proximity Operation of HY-2

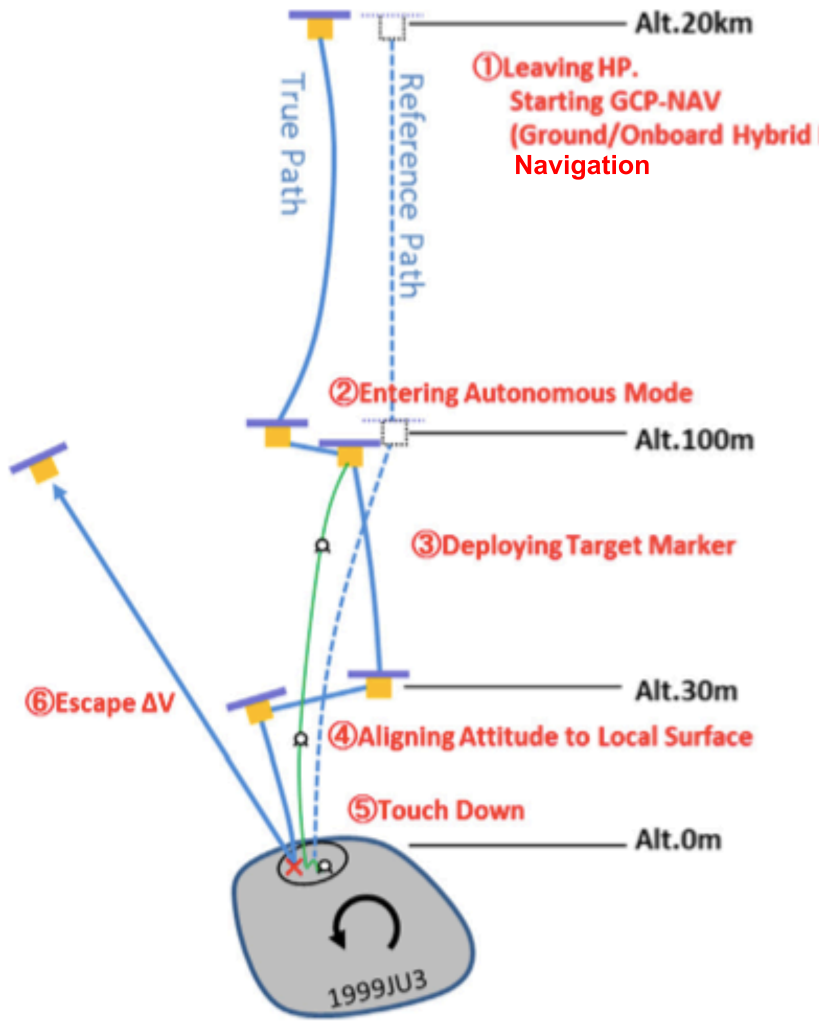
- Home position (HP) is 20 km above the asteroid facing the sub-Earth direction. All the off-HP operations, such as touch down, cratering, gravity measurement, and fly-around observation start from HP and return to HP after each event has ended.
- The in situ observation starts from the global mapping using ONC-T/W1. The surface temperature distribution and the surface composition distribution are also characterized using TIR and NIRS3.
- A few descent operations (~1 km) for closer observation in order to obtain a better resolution are planned to augment the global mapping output.
- Touch down consists of roughly three phases: (i) initial descent, (ii) autonomous descent/target marker deployment, and (iii) surface- relative descent and touch down.

Proximity Operation of HY-2 (cont.)

(i) **initial descent**: ground/onboard-based hybrid navigation called GCP-NAV is used. The vertical descent velocity is controlled on board to approximately 0.1–1m/s primarily using LIDAR. The horizontal position and velocity are determined from the ONC-T/W1 images in the ground-based process. Ground/onboard combined feedback loop is established with a 40-minute round-trip delay until the spacecraft reaches an altitude of 100 m.

(ii) autonomous descent/target marker deployment: is a fully autonomous mode in which ground intervention is impossible due to significant round-trip. The target marker (TM) is deployed at an altitude of 100 m, and the spacecraft attempts to track the landed TM using ONC-W1 and FLASH.

(iii) **surface-relative descent and touch down**: (cont.)

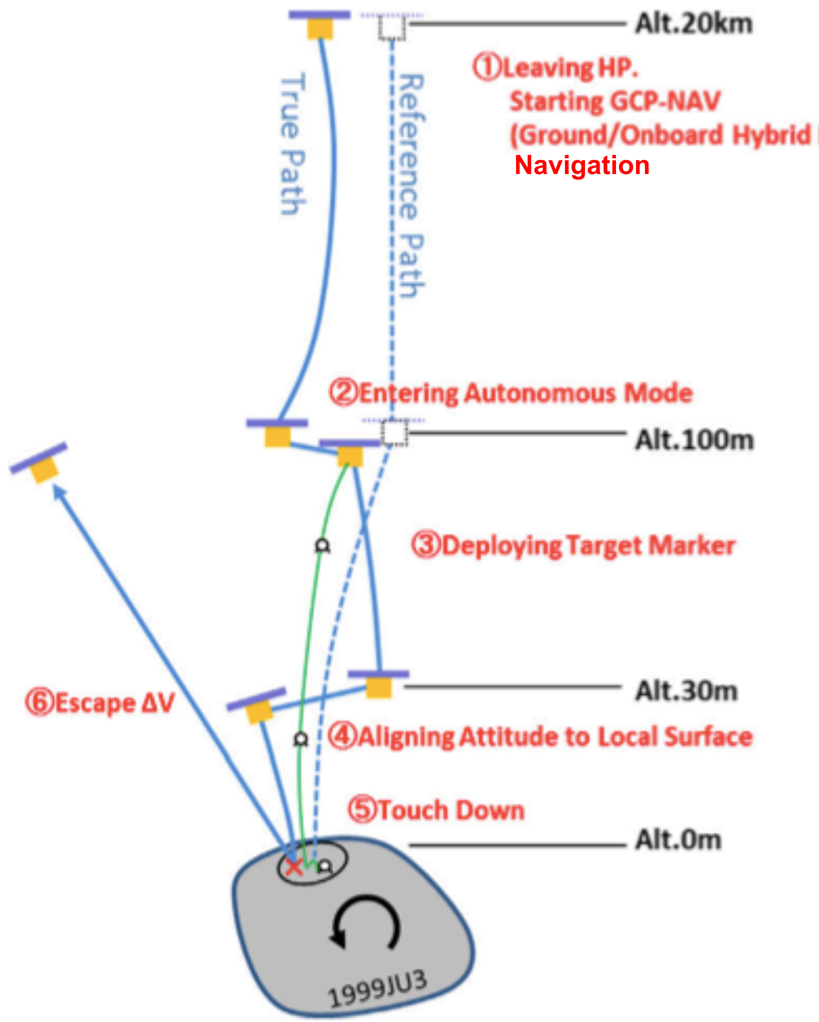


Sampling Operation Sequence

Proximity Operation of HY-2 (cont.)

(iii) surface-relative descent and touch down: at an altitude of 30 m, the LRF is turned on, and its four beams determine the local surface orienta- tion relative to the spacecraft. The spacecraft tracks the TM while aligning its attitude to the local horizon. The final 5-m descent is in free fall, and the touch down is to be detected by the bending of the SMP or the attitude rate change, which is immediately followed by projectile ejection and its impact.

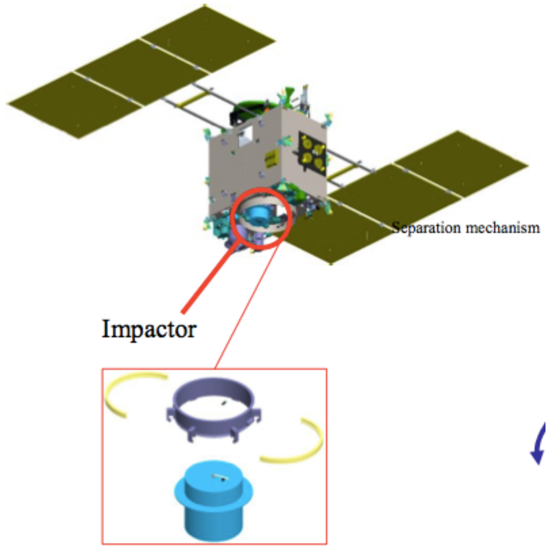
The escape ΔV is then triggered a few seconds later in the spacecraft +Z direction in order to ascend to the HP



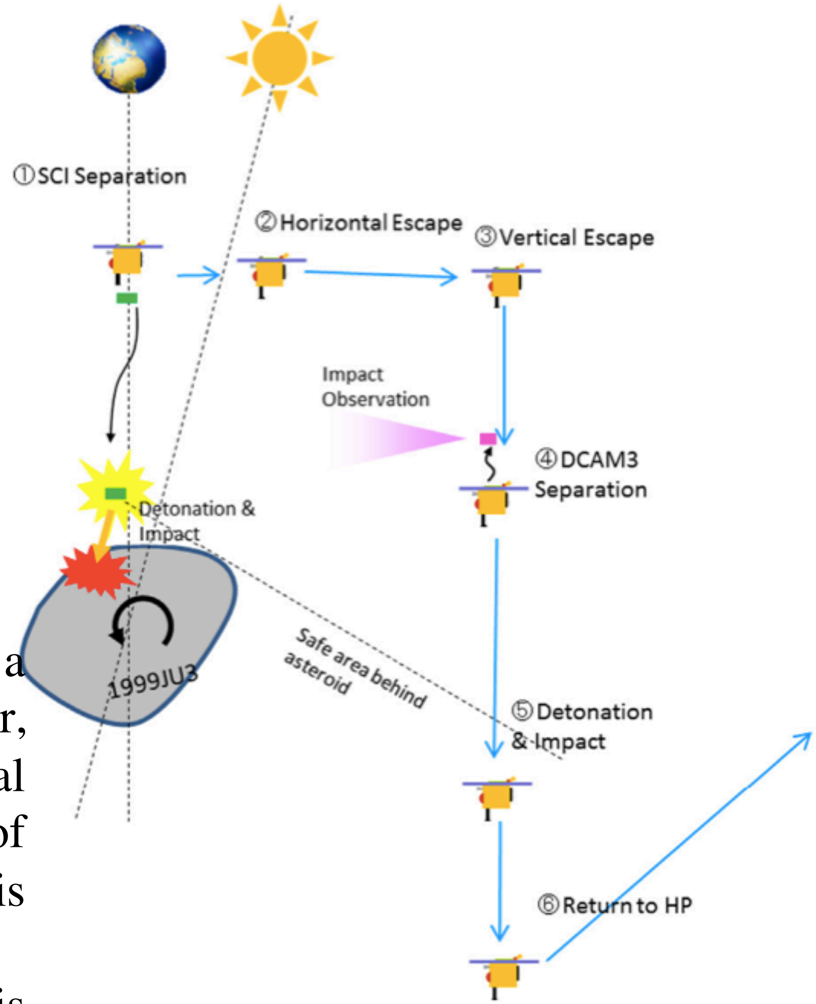
Sampling Operation Sequence

Small Carry-on Impactor (SCI)

Challenge to Investigate Fresh Sub-surface Materials



The SCI is a 18-kg payload and consists of a timer/ ignitor electronics, an explosive holder, and a 2-kg copper liner. The SCI is cylindrical and has a diameter of 300 mm and a height of 200 mm. Upon detonation, the copper liner is instantly accelerated up to 2 km/s.
The expected crater diameter is 2m, which is to be observed in detail after the spacecraft returns to the HP.



Cratering Operation Sequence

4. Summary and Future Expectations

Summary

1. After HY1, strong interest in sample & return from small bodies prevails to drive ISAS to conduct and prepare HY2 and other small body missions.
2. HY1/H2 experience was unique but its mission scenario will be applied to a variety of asteroid sample return mission. To provide a base-line design of sample return mission, mission design as well as spacecraft design are provided.
3. This is still not complete, but using the design iteration and the base-line design, I expect one can start thinking about a new small body mission.